CLAIMS

What is claimed is:

1. Apparatus for applying equalization to a complex-valued signal, the signal being single-axis (SA) modulated data, the apparatus comprising:

a linear predictive (LPR) filter characterized by a set of real-valued LPR parameters applied to the signal, wherein the set of LPR parameters are recursively updated based on one or more error terms to minimize output power of the LPR-filtered signal;

an equalizer configured as either a linear equalizer (LE) or a decision feedback equalizer (DFE) and applying an estimate of the inverse channel characteristics to the signal to generate an equalized signal, wherein:

i) the equalizer comprises a forward (FW) filter characterized by a set of FW filter parameters, a feedback (FB) filter characterized by a set of FB filter parameters, and a decision circuit generating hard decisions for the data of the equalized signal, and

ii) the set of real-valued FB parameters are initialized by the set of real-valued LPR parameters, the set of FW parameters are initialized with either values of a predetermined impulse response or values based on a function of a channel response; and the set of FW parameters and the set of FB parameters are recursively updated based on one or more error terms; and

an error term calculator configured to generate one or more error terms from one or more blind cost criteria based on real-part extraction.

2. The invention as recited in claim 1, wherein, for the equalizer:

the FW filter applies a FW function to the signal to generate the FW-filtered signal;

the FB filter applies a FB function to either soft decisions defined by the equalized signal or the hard decisions to generate a filtered decision; and

a combiner combines the filtered decision with a real-part of the FW-filtered signal to generate a new soft decision as the equalized signal.

3. The invention as recited in claim 2, wherein the decision device comprises:

a slicer configured to generate a symbol from the equalized signal as a hard decision; and

a carrier loop configured to detect and adjust a phase error of the received signal.

4. The invention as recited in claim 3, wherein the carrier loop applies the phase error to de-rotate the signal from the FW filter prior to real-part extraction.

5. The invention as recited in claim 3, wherein the carrier loop applies the phase error to de-rotate the signal applied to the equalizer.

6. The invention as recited in claim 3, wherein the equalized, received signal is adjusted, in gain, to generate an unbiased input signal to the slicer.

7. The invention as recited in claim 3, wherein the equalized received signal is scaled with a first scalar prior to its input to the slicer and each hard decision is scaled with a second scalar prior to its input to the FB filter.

8. The invention as recited in claim 7, wherein the first scalar is the reciprocal of the second scalar.

9. The invention as recited in claim 2, wherein the error term generator receives at least one of the equalized signal and the corresponding hard decision to generate the one or more error terms.

10. The invention as recited in claim 9, wherein the error term generator also receives the LPR filtered signal.

11. The invention as recited in claim 10, wherein the error term generator generates a single-axis output power (SA-OP) error term.

12. The invention as recited in claim 9, wherein the error term generator generates at least one of a decision directed (DD) error term, a constant modulus (CM) error term, and a single-axis CM (SA-CM) error term.

13. The invention as recited in claim 1, wherein, when operating, the equalizer is configured in one of at least three modes:

a first mode, wherein the set of LPR parameters for the LPR filter are recursively updated based on a single-axis output power (SA-OP) error term until the set of LPR parameters reach

steady-state values

a second mode, wherein the FW filter, decision circuit, and feedback filter are configured as the linear equalizer, and the set of FW parameters and FB parameters are adapted based on one or more error terms based on real-part extraction; and

a third mode, wherein the FW filter, decision circuit, and feedback filter are configured as the DFE, and the set of FW parameters and FB parameters are adapted based on the DD error term.

14. The invention as recited in claim 13, further comprising an operation controller, wherein the operation controller either selects the first mode, the second mode, or the third mode based on a performance measure.

15. The invention as recited in claim 14, wherein the performance measure is at least one of a signal-to-noise ratio, a cluster variance, a frame lock-status, a bit error rate, or an output power measure for the received signal.

16. The invention as recited in claim 13, wherein, in either of the second mode or the third mode, the set of FW parameters and the set of FB parameters are adapted based on a combination of the SA-CM error term and a decision-directed (DD) error term.

17. The invention as recited in claim 1, wherein the FB filter comprises a multiplexer (mux), a first feedback filter section, and a second feedback filter section, wherein:

the first FB filter section applies the set of FB parameters to soft decisions corresponding to the equalized, received signal;

the second FB filter section applies the set of FB parameters to scaled hard decisions generated by the decision circuit for the equalized, received signal, and

the mux either selects as the output of the feedback filter 1) an output of the first FB filter section when the equalizer is configured as the LE or 2) an output of the second FB filter section when the equalizer is configured as the DFE.

18. The invention as recited in claim 1, wherein data of the received signal includes a training sequence, and wherein the apparatus further comprises:

a training sequence correlator configured to correlate a conjugated signal from the LPR filter with a local sequence i) to detect the training sequence and ii) to generate an estimate of the set of FW filter parameters,

wherein the set of FW parameters is initialized based on the correlation.

19. The invention as recited in claim 1, wherein the received signal $r(n)$ is complex-valued, wherein the FW filter operates in the passband and the FB filter operates in the baseband, and wherein the recursive update at time n+1 of at least one of the sets of FW parameters ($f_j(n)$), and FB parameters ($h_j(n)$) employs the stochastic gradient descent rule:

$$\begin{aligned} f_j(n+1) &= f_j(n) - \mu r^*(n-j)e_{pb}(n) \\ h_j(n+1) &= h_j(n) + \mu\varphi(n-j)e_{bb}(n) \end{aligned}$$

where μ, 0< μ <1, is a step size, j is a parameter index, $r(\bullet)$ is the received signal, $\varphi(\bullet)$ is feedback regressor data, $e_{bb}(n)$ is a baseband error term, and $e_{pb}(n)$ is a passband error term.

20. The invention as recited in claim 1, wherein the FW filter operates in the baseband and the FB filter operates in the baseband, and the recursive update at time n+1 of at least one of the sets of FW parameters ($f_j(n)$), and FB parameters ($h_j(n)$) employs the stochastic gradient descent rule:

$$\begin{aligned} f_j(n+1) &= f_j(n) - \mu r^*(n-j)e_{bb}(n) \\ h_j(n+1) &= h_j(n) + \mu\varphi(n-j)e_{bb}(n) \end{aligned}$$

where μ, 0< μ <1, is a step size, j is a parameter index, $r(\bullet)$ is the received signal, $\varphi(\bullet)$ is feedback regressor data, and $e_{bb}(n)$ is a baseband error term.

21. The invention as recited in claim 1, wherein the signal is carrier modulated by data in accordance with a complex vestigial sideband (VSB) format.

22. The invention as recited in claim 1, wherein the signal is a digital television signal having its data encoded in accordance with an ATSC standard.

23. The invention as recited in claim 1, wherein the LPR filter operates in parallel with the equalizer, wherein the forward filter, feedback filter and decision circuit are configured as a decision feedback equalizer (DFE), the set of LPR parameters is adapted using an SA-OPA

update rule, and the set of LPR filter parameters $g_j(n)$ regularize the set of FB filter parameters $h_j(n)$ by minimization of the criterion $J_{reg}(h)$ as:

$$J_{reg}(h) = J_{combo}(h) + \lambda \sum_{j=1}^{N_g} \left| g_j(n) - h_j(n) \right|^2$$

where $J_{combo}(h)$ is a linear combination of CM and DD cost criteria and the recursive update of the FB parameters employs a LPR-regularized DFE update rule.

24. A method of applying equalization to a complex-valued signal, the signal being single-axis (SA) modulated data, the method comprising the steps of:

(a) applying a linear predictive (LPR) filter characterized by a set of real-valued LPR parameters to the signal

(b) recursively updating the set of LPR parameters based on one or more error terms to minimize output power of the LPR-filtered signal;

(c) applying either linear equalization (LE) or decision feedback equalization (DFE) to the signal to generate an equalized signal, wherein step (c) filters with a forward (FW) filter characterized by a set of FW filter parameters, and a feedback (FB) filter characterized by a set of FB filter parameters;

(d) generating hard decisions for the data of the equalized signal;

(e) initializing (e1) the set of real-valued FB parameters by the set of real-valued LPR parameters, and (e2) the set of FW parameters with either values of a predetermined impulse response or values based on a function of a channel response;

(f) recursively updating the set of FW parameters and the set of FB parameters based on one or more error terms; and

(g) generating one or more error terms from one or more blind cost criteria based on real-part extraction.

25. The invention as recited in claim 24, wherein step (d) generates each hard decision by the steps of:

(d1) combining i) the real part of the output of the FW filter and ii) the output of the FB

filter to form the equalized signal;

(d2) generating a symbol from the equalized signal as a hard decision; and

(d3) adjusting, by a carrier loop, a phase error of the received signal.

26. The invention as recited in claim 25, wherein step (d3) applies the phase error to de-rotate the signal from the FW filter prior to real-part extraction.

27. The invention as recited in claim 25, wherein step (d3) applies the phase error to de-rotate the signal applied to the equalizer.

28. The invention as recited in claim 25, further comprising the step of adjusting, in gain, the equalized, received signal to generate an unbiased input signal to the slicer.

29. The invention as recited in claim 25, comprising the steps of scaling with a first scalar the equalized received signal prior to its input to the slicer and scaling with a second scalar each hard decision prior to its input to the FB filter.

30. The invention as recited in claim 29, wherein the first scalar is the reciprocal of the second scalar.

31. The invention as recited in claim 24, wherein, for step (c), equalization occurs in one of at least three modes:

a first mode, wherein the set of LPR parameters for the LPR filter are recursively updated based on a single-axis output power (SA-OP) error term until the set of LPR parameters reach steady-state values

a second mode, wherein the FW filter, decision circuit, and feedback filter are configured as the linear equalizer, and the set of FW parameters and the set of FB parameters are adapted with one or more error terms based on real-part extraction; and

a third mode, wherein the FW filter, decision circuit, and feedback filter are configured as the DFE, and the set of FW parameters and the set of FB parameters are adapted based on a DD error term.

32. The invention as recited in claim 31, wherein, in either of the second mode or the third mode, the set of FW parameters and the set of FB parameters are adapted based on a

combination of an SA-CM error term and the decision-directed (DD) error term.

33. The invention as recited in claim 24, for step (f), recursive update at time n+1 of at least one of the sets of FW parameters ($f_j(n)$), and FB parameters ($h_j(n)$) employs the stochastic gradient descent rule:

$$\begin{aligned} f_j(n+1) &= f_j(n) - \mu r^*(n-j)e_{pb}(n) \\ h_j(n+1) &= h_j(n) + \mu\varphi(n-j)e_{bb}(n) \end{aligned}$$

where μ, 0< μ <1, is a step size, j is a parameter index, $r(\bullet)$ is the received signal, $\varphi(\bullet)$ is feedback regressor data, $r(n)$ is the received signal, $e_{bb}(n)$ is a baseband error term, and $e_{pb}(n)$ is a passband error term, wherein the FW filter operates in the passband and the FB filter operates in the baseband.

34. The invention as recited in claim 24 wherein, for step (f), recursive update at time n+1 of at least one of the sets of FW parameters ($f_j(n)$), and FB parameters ($h_j(n)$) employs the stochastic gradient descent rule:

$$\begin{aligned} f_j(n+1) &= f_j(n) - \mu r^*(n-j)e_{bb}(n) \\ h_j(n+1) &= h_j(n) + \mu\varphi(n-j)e_{bb}(n) \end{aligned}$$

where μ, 0< μ <1, is a step size, j is a parameter index, $r(\bullet)$ is the received signal, $\varphi(\bullet)$ is feedback regressor data, $r(n)$ is the received signal, and $e_{bb}(n)$ is a baseband error term, wherein the FW filter operates in the baseband and the FB filter operates in the baseband.

35. The invention as recited in claim 24, wherein, for step (f), recursive update of the set of LPR filter parameters ($g(z)$) uses an SA-OPA update rule and the set of FB filter parameters ($h(z)$) for the DFE employs an LPR-regularized DFE update rule for the minimization of criterion $J_{reg}(h)$ as:

$$J_{reg}(h) = J_{combo}(h) + \lambda \sum_{j=1}^{N_g} \left| g_j(n) - h_j(n) \right|^2$$

where $J_{combo}(h)$ is a linear combination of CM and DD cost criteria.

36. The invention as recited in claim 24, wherein, for step a), single-axis modulated signal is the carrier modulated by the data in accordance with a vestigial sideband (VSB) format.

37. The invention as recited in claim 24, wherein, for step a), the single-axis modulated signal is a digital television signal having its data encoded in accordance with an ATSC standard.

38. The invention as recited in claim 24, wherein data of the received signal includes a training sequence, and wherein step (e2) comprises the steps of:

(e2i) correlating a conjugated signal from the LPR filter with a local sequence;

(e2ii) detecting the training sequence; and

(e2iii) generating an estimate for the set of FW filter parameters based on the correlation of step (e2i).